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Modeling and Experimental Verification of a DEAP's based 2-D rotational positioner

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Abstract:

A feasibility study into the appropriateness of using a laminated dielectric electro active polymer (DEAP) film, called PolyPower^{TM}, for two dimensional rotational positioning is reviewed in this work. The maximum strain in the film is limited to 50 *%* and the maximum applied voltage is currently limited to 3000 *V*. This work will examine the ability of positioning a shaft coupled to a laser beam pointer in *x-y* direction which will provide insight into (a) the practicality of using the material for two dimensional rotational positioning and (b) to highlight feasible positioning applications.

A test setup was designed and a series of experiments carried out to investigate two dimensional rotational positioning using DEAP material. The initial mechanical strain level for the actuators was 15 *%* operating at a maximum applied voltage of 2.5 *kV* with five different levels of applied voltage to each of the active actuators with 0.5 *kV* steps. For each, of the testing combinations the angle target was determined and results compared with the model of the two dimensional positioner. The feedback of positioner was not addressed in this work; through the relevant control theory which will be implemented in the future work will be discussed.

Keywords: Two dimensional rotational positioner, dielectric electro active polymer, Active actuator, Passive actuator, eyeball, Experimental verification.

1.0 Introduction

Two dimensional rotational positioning (or eyeball positioning) shown in (Fig. 1) describes any process by which an application is positioned in *x-y* plane. The application could be in the future car headlight, front passenger mirror, adaptive lighting systems airfoil and robotics rotational joints [4]. The possible advantage of using dielectric electro active polymer (DEAP) materials for two dimensional positioning mirror the advantages that researchers find attractive for designing DEAP-based actuators, namely that materials allow large force to mass ratio combined with silent operation and a very low power consumption.

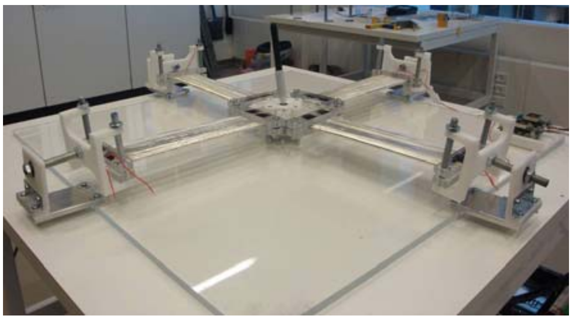


Fig. 1: *The 2-D rotational positioner setup*

Centro Interdipartimentale di Ricerca at the University of Pisa carried out the most reported research into developing DEAP- based actuation mechanism for the eyeball. Their initial development work in the F.A.C.E. (Facial Automaton for Conveying Emotions) research project concentrated on building a bio inspired actuation mechanisms using eyeballs to replicate actions exerted by the main ocular muscles. With two actuators connected to the eyeball via inextensible tendon-like wires to enable the rotation in one direction only. The eyeball was shown to be capable of rotating $\pm 25°$ using 54mm actuators [1].

Danfoss PolyPower A/S has been researching dielectric electro active polymer (DEAP)-based technology for a number of years, using smart compliant electrode technology [5] in conjunction with a silicon elastomer [6]. So far the company has concentrated on developing an automatic manufacturing facility for their PolyPower^{TM} material as well as designing and fabricating PolyPower^{TM} actuators. Two actuator types currently exist; a pre-strained 'pull'-type actuator and a core free tubular 'push' actuator with no pre-strain.

This work investigates the feasibility of using the PolyPower^{TM} DEAP material for the eyeball positioning. The maximum strain in the film is limited to 50% and the maximum applied voltage is currently limited to 3000 *V*. This work will examine the ability of positioning a shaft with a laser beam in x-y direction which will provide insight into (a) the practicality of using the material for two dimensional rotational positioning and (b) to highlight feasible positioning applications. The following two objectives are addressed:

The development of a detailed mathematical model that describes the dynamic behavior of the system

Building and testing of a practical setup which enable to control the Eyeball positioner, measuring the angles and validating the results

This work concentrates on the modeling and experimental verification of the state of art Eyeball positioner. The closed feedback loop control is not addressed in this, though the theory of applying it will be discussed briefly.

2.0 The DEAP film

The PolyPower™ dielectric EAP film consists of a silicone-based elastomer, Elastocil®RT 625 produced by Wacker[6] in conjunction with smart compliant electrode technology, whereby metalized electrodes are imprinted on the corrugated elastomer surface. The bottom of the sheet is flat. The corrugation is essential in providing a degree of electrode compliance when the elastomer elongates in the axial direction due to an applied voltage. The film is produced in very thin sheets, 25-30 *μm*.

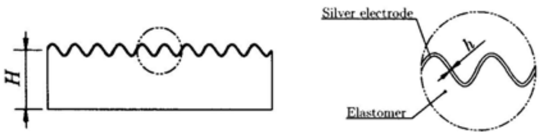
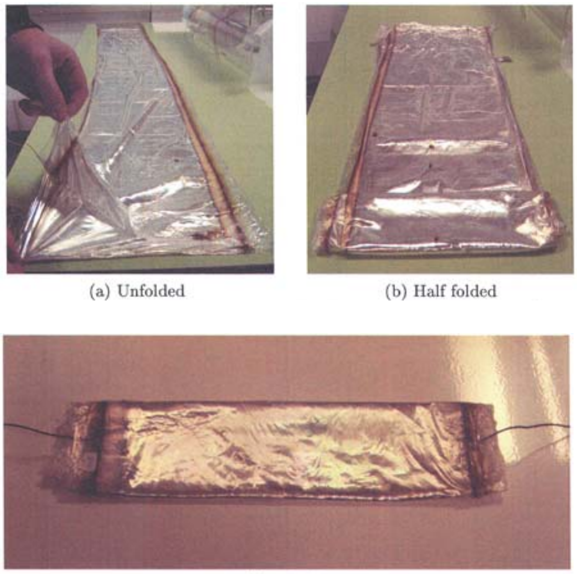


Fig. 2: *Elastomer with silver electrodes following the corrugated surface.*

About 80 *nm* of silver is deposited on the corrugated surface; see figure 2, using a physical vapour deposition (PVD) process. Two single-sided composite films are placed back-to-back to form the laminate from which both types of PolyPower-based actuators, the 'pull' and 'push' actuators, are constructed. The simplest type of actuator - the 'pull' actuator, will only be used for this modelling and experimental study. This choice simplifies the modelling of the positioner and also allows a straightforward realisation of the mechanical set-up design.



(a) Unfolded (b) Half folded

(c) Folded

Fig. 3: *Constructing a PolyPower™ 'Pull' Actuator.*

Figure 3 shows the stages in the building of the PolyPower™ 'pull' actuator. An initial sheet of DEAP material is taken (figure 3(a)) then half folded (figure 3(b)) and finally fully folded (figure 3(c)) to produce the 'pull' actuator. Connectors are then attached at both ends as indicated in figure 3(c). The 'pull' actuator is nominally 200 *mm* long.

Smart compliant electrode technology constrains the width of the DEAP material, $w = w_0$, so that any contraction in the material thickness due to the electrostatic forces is converted into an elongation in the length direction, l, see figure 3(c). The smart compliant electrode technology also limits the maximum strain that the 'pull' actuators can undergo to < 35%. For strains up to this maximum value the Mooney-Rivlin model is used to describe the viscoelastic properties of the material[7]. For the PolyPower™ 'pull' actuators (from now on referred to as the DEAP element) the resulting stresses in the width, w, length, l, and thickness, t, directions using the Mooney-Rivlin model can be written as:

$$\sigma_w = 0, \quad \sigma_l = -\sigma_t = \left(2D_1 + 2D_2\right)\left(\alpha^2 - \frac{1}{\alpha^2}\right) \quad (1)$$

where D_1 (= 0.07 x 10^6 *MPa*) and D_2 (= 0.04 x 10^6 *MPa*) represent the Mooney-Rivlin constants[7] and α represents the stretch ratio. For incompressible material the stretch ratio is defined as:

$$\alpha = \frac{l}{l_0} = \frac{t_0}{t} = 1 + e \quad (2)$$

where l_0 represents the original length of the material, t_0, the original thickness and e the strain in the length direction.
For the DEAP element electrostriction is negligible with any elongation being attributed purely to the Maxwell forces resulting from an applied voltage. The stress balance in the case of constrained width, without any loading, F, is:

$$\sigma_{\max} = \sigma_l \Rightarrow \left(2D_1 + 2D_2\right)\left(\alpha^2 - \frac{1}{\alpha^2}\right) = \varepsilon_0 \varepsilon_r \left(\frac{V}{t}\right)^2 \quad (3)$$

where ε_r represents the relative permittivity of the DEAP material, ε_0 represents the absolute permittivity and V is the applied voltage. This expression can be re-written using, the stretch ratio, $\alpha = t_0/t$ as:

$$\left(2D_1 + 2D_2\right)\left(\alpha^2 - \frac{1}{\alpha^2}\right) = \varepsilon_0 \varepsilon_r \left(\frac{V}{t_0}\right)^2 \alpha^2 \quad (4)$$

(4) can be solved analytically to give the following expression for the stretch ratio, α, of the actuator and, from (2), the corresponding strain of the DEAP element:

$$\alpha = \left(1 - \frac{\varepsilon_0 \varepsilon_r}{\left(2D_1 + 2D_2\right)}\left(\frac{V}{t_0}\right)^2\right)^{-\frac{1}{4}} \quad (5)$$

The capacitance change of the DEAP element as a function of applied voltage is, $C_f = C_i\, \alpha^2$, where C_i indicates the initial capacitance and C_f the final capacitance.

3.0 Modelling the Eyeball positioner

There are actually two ways to oversee the operation of the Eyeball positioner depending on the application which will be used for [3]. For some applications, static modelling can be used to describe the relation between the desired angles and the applied voltage. On the other hand, dynamic modelling is necessarly when the frequency element is introduced. In this work, Static and Dynamic modelling, Linear to angular translation and control theory will be addressed.
Static modelling: The strain levels for the material are limited to 10%, a linear relation for the strains is assumed to simplify the modeling of the Eyeball positioner. The longitudinal stress can be found by applying Hooke's law which is defined by:

$$\sigma_l = Ye \quad (6)$$

where Y is the young's modulus '1.1 MPa' and e is the strain, equation (6) can be written as:

$$e = \frac{\sigma_l}{Y} \quad (7)$$

Inserting equation (3) for the longitudinal strain in equation (7) to get:

$$e = \frac{\varepsilon_r \varepsilon_0 V^2}{Y.t^2} \quad (8)$$

The capacitance of the material can be described using the fundamental plate capacitance formula:

$$C = \frac{\varepsilon_r \varepsilon_0 A}{t} \quad (9)$$

Where $\varepsilon_r, \varepsilon_0$ are the relative, permittivity coefficients respectively, rewriting equation (9) to:

$$\varepsilon_r \varepsilon_0 = \frac{Ct}{A} \quad (10)$$

Equating the equation (8) and (10) to get a relation between the applied voltage (input) and the elongation (output):

$$e = \frac{CV^2}{AtY} \quad (11)$$

(11) Can be re-written as:

$$e = \frac{C.V^2}{Y.v} \quad (12)$$

Where v is the volume which is define by the Area x thickness
Dynamic modelling: In order to model the frequency dependent strain – voltage relation, the dynamic model is considered. This was done by modelling the DEAP material as spring-damper system which enable writing the equilibrium of force by applying newton's 2nd law as shown in equation below:

$$m\frac{d^2x}{dt^2} = f_g - f_{vis\cos e} - f_{spring} + f_{\max vell} \quad (13)$$

Where the respective forces 'gravitational, viscous, spring & Maxwell' contributions are defined by:

$$f_g = mg \quad (14)$$

$$f_{vis\cos e} = \gamma \frac{dx}{dt} = \gamma x_0 \frac{d\alpha}{dt} \quad (15)$$

$$f_{spring} = A_{yz}\sigma_{hooke}$$
$$= AY(\alpha - 1) = yt_0 Y(\alpha - 1) \quad (16)$$

$$f_{\max vell} = A_{yz}\sigma_m = yt\frac{1}{C_0 v}\frac{q^2}{\alpha^2}$$
$$= y\frac{t_0}{\alpha}\frac{1}{C_0 v}\frac{q^2}{\alpha^2} = \frac{yt_0}{C_0 v}\frac{q^2}{\alpha^3} \quad (17)$$

Inserting equations (14), (15), (16), (17) in equation (13) to get:

$$mx_0 \frac{d^2\alpha}{dt^2} + \gamma x_0 \frac{d\alpha}{dt} + yt_0 Y(\alpha - 1) - mg = \frac{yt_0}{C_0 v}\frac{q^2}{\alpha^3} \quad (18)$$

Neglect: $R\dfrac{dq}{dt}$ and $L\dfrac{d^2q}{dt^2}$ and the equation and insert $\alpha = e+1$ to get:

$$mx_0\frac{d^2e}{dt^2}+\gamma x_0\frac{de}{dt}+\left(yt_0Y-\frac{yt_0C_0}{v}V(t)^2\right)e-mg = \frac{yt_0C_0}{v}V(t)^2 \quad (19)$$

Assuming $yt_0Y >> \dfrac{yt_0C_0}{v}V(t)^2$ and disregard mg to get final form denoted in the equation below:

$$mx_0\frac{d^2e}{dt^2}+\gamma x_0\frac{de}{dt}+yt_0Ye=\frac{yt_0C_0}{v}V(t)^2 \quad (20)$$

Solving equation (20) for the strain to get:

$$e(t)=\frac{e_{\max}}{2}+\frac{e_{\max}}{2}\cos(2wt) \quad (21)$$

w is the frequency and $e_{\max}$ is the maximum strain at defined bias voltage, could be also defined as the static strain.

The last step of the modelling is to find the relation between the angle and the other parameters, the angle formula will be used to design the control of the Eyeball positiner. The assumption in this case is done by neglecting the deflection effects introduced from the movement in the opposite direction, hence, the strain can be defined as:

$$e = D.\vartheta \quad (22)$$

D is the distance from the center of the rotation to the coupling point, substituting for the strain to get:

$$\vartheta=\frac{C.V^2}{Y.v.D}\ \text{(rad), or}\ \vartheta=\frac{C.V^2.180}{Y.v.D.\pi}\ \text{(degree)} \quad (23)$$

4.0 Results

The Eyeball electromechanical setup was used for validation purposes [3]. The time response of the Eyeball positioner is found to be 58 msec in the forward/backward motion for the used 133 nF capacitance (see Fig. 4.).

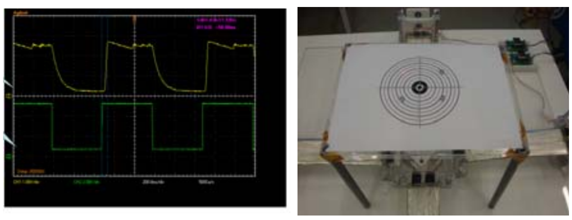


Fig. 4. *(left) The time response (right) The surface used for measuring the angle*

The modeling error shown (see Fig. 5) is found to be within 5% for the ten measurements using voltage range of 0.5→2.5 *KV*.

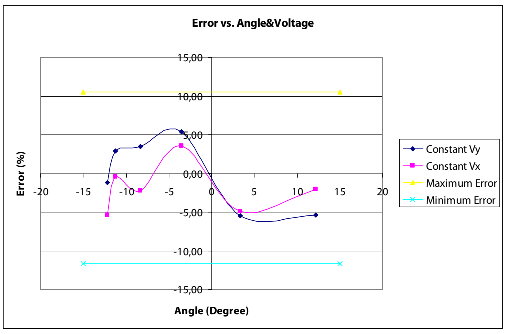


Fig. 5: *Comparison of Measured and Modeled angles for the Experimental Tests*

5.0 Conclusion

The feasibility of developing a 2D rotational positioner was investigated in this work; the electromechanical setup was based on Dielectric Electro Active Polymers pull actuators. The conceptualization and the implementation of the Eyeball positioner setup using DEAP shows a good future potential, the performance of the system is relative on the size of the spherical bearing and the distance of coupling. The maximum angle achieved by the 2D rotational positioner was 12 degrees in x-y directions. This was obtained at 2.5 KV using four actuators mounted to reach the equilibrium of forces with a strain of 15%.

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